Articles from Computational Culture

Sensing an Experimental Forest: Processing Environments and Distributing Relations

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Abstract
The use of wireless sensor networks to study environmental phenomena is an increasingly prevalent practice, and ecological applications of sensors have been central to the development of wireless sensor networks that now extend to numerous 'participatory' applications. How might environmental sensing projects be understood as giving rise to new practices for sensing environmental processes, and what are the implications of these new modalities of sense? Working through posthuman media theory, as well as engaging with Alfred North Whitehead's approach to 'experience' as something that is embodied across human and more-than-human subjects, the paper considers how distributed sensor technologies contribute to new sensory processes by shifting the relations, entities, occasions, and interpretive registers of sensing. Focusing specifically on one environmental sensor test site, the James Reserve in California, the paper suggests that these experimental environmental sensor arrangements mobilize distinct sensing practices that are generative of new environmental abstractions and entities. How do the interpretative practices that develop through experimental environmental sensing then inform environmental matters of concern? What are the implications of these experimental environmental sensing arrangements as they migrate into policy, and as they inform participatory sensing processes?

Environmental Sensing
Surrounded by the San Bernardino National Forest and situated within the San Jacinto Mountain Range in California, there is one particular patch of woods that is distinct in its ecological processes. This forest is equipped with embedded network sensing that digitally detects and processes environmental phenomena, from microclimates to light patterns, moisture levels and CO_2 respiration in soils, as well as the phenology, or seasonal timings, of bluebirds and auditory signatures of woodpeckers. These multiple modes of experimental forest observation are part of a test site for studying sensors in situ. A 'remote sensing lab,' the University of California James Reserve is an ecological study area that has hosted field experiments since 1966. The use of this ecological study area to test electronic sensors developed through the Center for Embedded Networked Sensing (CENS) research project is at once a continuation of experimental ecological practices that have sought to understand the multiple environmental processes in this area, as well as a shift in the technologies and practices for studying environments. The question that emerges here is: when the ecological experiment changes, how then do experiences also change?

This notion of experimenting and experiencing as springing from the same modality is put forward by Isabelle Stengers in her discussion of Alfred North Whitehead, where she coins 'a (French-inspired) neologism' that does not draw a 'clear distinction between the terms "experience" and "experiment" as there is in English.' This merging of terms is also a critical way for describing the approach of Whitehead, which is characterized by a crossing-over of experience and experiment, where experimenter and experiment are part of a unified and concrete occasion.[1] This point of entry is important for this discussion of sensors, as it immediately points toward a consideration of sensors not as instruments sensing something 'out there,' but rather as devices for making present and interpretable distinct types of ecological processes. These processes are rendered computationally, and they draw together a wide range of experiencing entities that begin to inform new arrangements of environmental sensing.

The use of wireless sensor networks to study environmental phenomena is an increasingly prevalent practice. Sensing projects encompass studies of seismic activity, the health of forests, maps of contaminant flow, as well as the tracking of organisms from dragonflies and turtles to seals and elephants, which provide indicative sensor data of environmental processes. At a time when ubiquitous computing is extending to all aspects of everyday life, where the Internet of Things promises to have your refrigerator communicating with supermarkets, and smart city designs propose to harvest your location data to ensure your roast-chicken dinner is prepared on time, sensing environments for ecological study is just one set of practices within a larger project of programming environments through distributed modes of computation. [2] Sensor networks arranged over static and mobile platforms and widely distributed throughout environments are the common thread throughout these projects, but the deployment of sensors within ecological study sites has been one of the key areas for sensor research and development.

Although a range of research has been conducted on ubiquitous computing and the Internet of Things,[3] less has been written in the context of digital media theory or science and technology studies about the ways in which understandings and practices of environmental science have shifted through sensor systems, and how these shifts have also had recursive effects on more 'participatory' sensor projects. While sensors and sensor systems were initially developed for use in military contexts, wireless and embedded sensor systems have further developed through ecological study, which has in turn provided an additional basis for deploying sensor systems within social media and citizen-sensing contexts. [4] This paper focuses on the use of sensors for study in environmental science in order to begin to consider how these sensing practices might inform parallel sensing practices.

Situated within the context of these ubiquitous computing developments, this paper specifically focuses on the distinct forms of sensing that emerge in relation to monitoring environmental phenomena. One key advantage that sensor systems are meant to provide is the ability to understand the complex interactions and relations within ecosystems in greater detail. Ecological relations emerge in higher resolution because sensors monitor and make available aspects of environmental processes as they unfold over time rather than as more discrete moments; and because more data are available for generating models of complex interactions. But this study asks how the ecologies that emerge for study through more continual sensor observation are not simply the result of increased data output and processing, but might also be understood as emergent sensory relations articulated across humans, more-than-humans, environments and devices. In what ways do distributed sensor technologies contribute to new sensory processes by shifting the relations, entities, occasions, and interpretive registers of sensing? How do the interpretative practices that emerge in experimental environmental sensing then inform environmental matters of concern? And what are the implications of these experimental environmental sensing arrangements as they migrate into policy, and as they inform participatory sensing processes?

In order to consider these questions, I first give an overview of the increasing use of sensors for monitoring environments and studying environmental change. The generation of more and higher-quality data is seen as critical to developing more advanced insights into how environments are transforming, and so the sense data produced through these projects are often gathered for the purposes of informing science and policy, in addition to testing prototype computational technologies in the field. Environmental monitoring can bring with it a sense of increased responsibility, and the commonly used phrase, 'all eyes on earth,' is a way of articulating the watchful concern that sensors are seen to embody and operationalize through the continual observation of environmental processes.

But sensors connect up more than just a network of human eyes or their correlative. This paper then draws on posthuman media theory to move beyond human-centric interpretations of (computational) technology; and engages with Alfred North Whitehead's approach to experience as something that emerges across human and more-than-human subjects. As Whitehead suggests, perceiving subjects are neither exclusively human nor pre-given, but combine as feeling entities through actual occasions.[5] In this way, sensors might also be understood not as detecting essential external phenomena, but as part of generative processes for making interpretive acts of sensation possible—and for articulating emerging environments as matters of concern. This is a way of saying that interpretation matters, that experience to be interpreted emerges across multiple registers and entities; and also that interpretation is part of a processes whereby things come to matter as objects of importance or relevance.[6]

Based on a consideration of the distinct articulations of sense across more-than-human and environmental processes, this paper moves to focus specifically on the use of embedded networked sensors at the James Reserve ecological study site. Drawing on fieldwork carried out at this test site for studying sensors in situ, as well as an analysis of online records of sensor data, I discuss new formations of distributed sense that emerge through these experimental forms of environmental sensing. Part of the way in which sensors might be understood as operative within distinct registers of experience is as distributed computational technologies. Sensors are distributed in at least two ways: both in terms of their spatial distribution, by monitoring environments in a widespread and localized way; and in terms of the distributions of experience that generate sense data and interpretations.[7] If we take seriously Whitehead's suggestion that sensing entities emerge through experiences and that they are inseparable from occasions of experience, then how do experimental environmental sensor arrangements mobilize distinct sensing practices that are generative of new environmental abstractions and entities?[8]

As Whitehead suggests, abstractions are not separate from concrete things, but rather inform 'the process of concrescence' and provide a 'lure for feeling.'[9] The concrescences that emerge here might be understood not just as scientists-devices-flora-and-fauna, but also as relations that emerge through data sets and algorithmic processes, across sedimented environmental effects, and through responsive modes of ecological action. The coming together of an experiment then presents the possibility for distinct experiences and subjects to emerge. Sensing an experimental forest is not about detecting information out there, but about 'tuning' the subjects and conditions of experience to new registers of becoming, as well as new matters of concern. Tuning is a way to describe the co-emergence of agencies within experiments, and the difficult process of developing facts or matters of concern within such experiments.[10] This paper then sets out to provide an understanding of the dynamic, distributed and multiple modes of computationally sensing environments that might provide insights for a more cosmopolitical participation in sensing environments, where sensing is a process of tuning and experiencing that is multi-directional, and involves multiple subjects.[11]

Instrumenting the Earth

The use of instrumentation, from bird ringing to anemometers, within ecological study has a longer history than the more recent use of wireless sensor systems.[12] However, the miniaturization and faster processing speeds of sensors have contributed to their increasing use as instruments within ecological study.[13] Sensor systems—composed of relatively small-scale in situ sensors and actuators that are able to collect and transmit data through wireless connections, as well as undergo remote reprogramming—have been described as nothing less than another 'revolution' on par with the rise of the Internet.[14] These imagined and actual transformations involve extending computational capacities to environments through sensors, where objects and phenomena are transformed into sensor data and made manageable through those same computational architectures.

In related literature, wireless sensor networks have also been described as a revolution in scientific instrumentation, similar to the telescope and microscope, where a new order of insights might be realized. But instead of probing outer or inner space, sensor networks are seen to operate as 'macroscopes,' which enable a new way 'to perceive complex interactions' through the high density and resolution of temporal and spatial monitoring data.[15] While issues related to providing a reliable power source, ensuring the robustness of hardware, and maintaining the validity and manageability of large data sets remain, sensor systems are seen to present the possibility for understanding environmental processes and relations more thoroughly by providing records and real-time data that are more detailed than existing modes of data collection, including remotely sensed and manually gathered data that may be at a much larger scale or more discrete moments in time. A background of relations may then be connected up and made evident through these sensing devices.

A wide range and number of projects now employ sensors for environmental monitoring, from bird migration and nesting to the social life of badgers, and from water quality monitoring to phenological observations, as well as acoustic sampling of volcanic eruptions and monitoring of microclimates in redwood forests.[16] One of the key projects within sensor systems development—a 2003 study of Leach's Storm Petrels at Great Duck Island, a wildlife preserve in Maine—established that 'habitat and environmental monitoring is a driving application for wireless sensor networks.'[17] This sensor project employed static sensor nodes and patches, with 'burrow motes' and 'weather motes'—or sensor nodes—to study the underground nesting patterns of migrating birds. As with many similar and subsequent sensor deployments, this project generated more detailed data on previously unobserved ecological phenomena and relationships, while also providing a testbed for experimenting with the system architecture of sensor networks. The ecological relationships observed—or sensed—are in many ways coupled with the capacities of sensor networks, which similarly are adapted to and 'learn' from the processes under study. The 'tuning' of sensor networks may then take place not just between scientists and devices, but also between devices, code and ecological processes.

At the same time that sensor observations are intended to provide more detailed renderings of phenomena on the ground, they also contribute to multi-scalar and widely distributed approaches to environmental sensing, including remote sensing by satellites and airborne observations. Multiple 'observatories,' together with long-term ecological research sites (LTERs), and the U.S. National Ecological Observatory Network (NEON), which attempts to synthesize sensor data across the United States, collect and provide ongoing sensing data, often across scales and from diverse modes of sensor input for wider and more detailed views on environmental processes and to study the effects and possible impacts of environmental change.[18] While a site-specific sensor project may study the detailed relationship between birds' nesting behavior in relation to microclimate and multiple other environmental factors, this same study may benefit from climate data resources or may contribute to climate monitoring programs. The sense data gathered may have the potential to elucidate environmental relations within a particular area of study, as well as across expanded and yet-to-be-gathered data sets—as long as the data to be compared are of compatible formats.

Just as sensing systems are proliferating, numerous attempts are then underway to amalgamate and make sense of the many forms of data—a key 'cyberinfrastructure' task—since the multiple formats and provenances of data may mean that they are rendered meaningless for ongoing use and study if not consistently handled.[19] Sensor-gathered data sets, which are typically 'heterogeneous,' are increasingly brought together not just in larger data networks, but also in mapping platforms where fine-grain sensor data provides a 'ground-truth' to coarser remote-sensing and field-gathered data. From Microsoft's SenseWeb to the DIY sensing platform Cosm (formerly Pachube), such platforms intend to consolidate environmental sensor inputs.[20] The range of possible sensor inputs is illustrated by one Microsoft graphic, 'Instrumenting the Earth,' which outlines twenty different modes of sensor input, from snow hydrology and avalanche probes to citizen-supplied observations and weather stations.[21] Innumerable potential points and processes in the environment become the basis for sensor input, and it is from these delineated sites of input that newly observed relations might be studied, articulated or managed.

While these sensing projects and networks have been under development within universities and public institutions, technology companies working individually or often in collaboration with universities are developing a whole range of sensor network systems. These projects range from Nokia's 'Sensor Planet,' to IBM's 'A Smarter Planet,' HP Labs' 'Central Nervous System for the Earth' (CeNSE), and Cisco's 'Planetary Skin' (in collaboration with NASA, the University of Minnesota, Imperial College, and others).[22] Governments and their militaries are also investing in the development of sensor networks, with whitepapers and research issuing from the EU, China, and the US DARPA, among others.[23] Many of these sensing projects raise ethical issues related to surveillance, while still other projects are enabling new forms of resource exploitation. The project of monitoring and managing environmental relationships continues to be a way in which the governmentality—and even environmentality—of sensor systems unfolds, where sensor capacities may point toward particular relations to manage or sustain in distinct ways.[24]

All together, these environmental sensing systems variously undertake a project of instrumenting or programming the Earth.[25] Within a sensor-ecology imaginary, the planet might be understood as an entity to be sensed and transformed into data. Improved sensing capabilities have come to be seen as critical to advancing understandings of environmental change, while also indicating ways of acting (whether through automated systems or environmental policy) in response to that data. With small-scale, distributed and pervasive computation embedded in environments, new relationships not just to studying, but also to managing environments emerge, since sensor systems computationally describe and capture environmental processes, while also providing the promise to 'design and control these complex systems.'[26] On the one hand the argument here is that increased amounts of data about environments allow for the greater management of environments. Data are descriptive measures capturing environmental transformations out there. But from a Whitehead-influenced perspective, it could be argued that sense data are less descriptive of pre-existing conditions, and more productive of new environments, entities and occasions of sense. The ways in which phenomena are delineated as sense data are one part of this operation of becoming sensible, but the ways in which sensory monitoring gives rise to new formations of sense within and through data and computational modes of relating as well as across humans, more-than-humans and environments also mobilize distinct distributions of sense. Since sensor networks are seen to offer distinct insights into the complex interactions and processes within environments, then the ways in which these relationships are joined up, articulated, and transformed into new observational capacities matters.[27]

Distributing Sense

The initial developments of ubiquitous computing are often attributed to Mark Weiser's 1991 suggestion for computation to move from desktops to the environment, so that computational processes would become a more integrated and invisible part of everyday life.[28] Yet another possible reference point could be Alan Turing's 1948 ruminations on how to build 'intelligent machinery' with sensing capacities on par with humans. Turing reviews the options for such a project, first considering how to atomize every part of the human ensemble and replace it with equivalent machinery. Emulating human vision, speech, hearing and mobility, such a contraption 'would include television cameras, microphones, loudspeakers, wheels and "handling servo-mechanisms" as well as some sort of "electronic brain."'[29] This project would inevitably be 'of immense size,' Turing notes, 'even if the "brain" part were stationary and controlled the body from a distance.' But data would not enter the thinking machine through its remaining static, and so 'in order that the machine should have a chance of finding things out for itself it should be allowed to roam the countryside.' But in such a scenario 'the danger to the ordinary citizen would be serious.' Add to this all of the usual activities of human interest, and such a machine would be altogether unwieldy. Turing's more practical recommendation is to behead the body, to work with the brain as the critical site of processing, and later attend to the sensory apparatus.[30]

Even if Turing's proposal does consolidate the 'thinking machine' into a central and seemingly Cartesian apparatus, his thought experiment on the sensing body in pieces and distributed throughout the countryside remains a potent figure for ubiquitous computing. What is striking about Turing's example is the way in which the thinking machine even when distributed would emulate the human body, which serves as a template for understanding how sensory data would be captured and centrally computed. While computational sensing technology can now be understood as more than a double of or prosthesis for the human sensing body, Turing's figure of the body in pieces raises questions about how particular distributions of sense might reconfigure the sites and processes of sensation. Could such distributions of sense point toward modes of sensation where computation reassembles not as a singular sensing subject, but rather as a processual and multi-located experience comprised of numerous sensing entities? In this way, sensing also assembles not as a mental or cognitive operation, but as an environmental and relational articulation across multiple bodies and sites of sensing.[31] Within Turing's example of the sensing body in pieces, this could mean that we attend not to how the body might reassemble toward human perception and functionality, but rather to how the 'countryside' and the many inhabitants, processes and processors of this distributed and distributive milieu begin to rework how the thinking-sensing machine captures, configures and acts upon its inputs.

Perception in the world

Turing's distributed sensing apparatus then points to the distributed processes that make sensing possible, even if the sites of sensation do not return to a coherent human processor. Indeed, as Whitehead suggests, perception might be understood to be in the world and distributed through innumerable nonhuman processes—it is not the special preserve of a human decoding subject. Instead, multiple participants unfold a distinct experience of the world, independently but contemporaneously within an immanent series of events.[32] At the same time, the excitations of environments are fused to all modes of 'matter,' where 'the environment with its peculiarities seeps into the group-agitations which we term matter, and the group-agitations extend their character to the environment.'[33] 'There are numberless living things,' Whitehead writes, that 'show every sign of taking account of their environment.' [34] This taking account of environments is a way of capturing what is relevant, and through being affected also transforming environments and relations.

Sense data might be seen as a concrescence of multiple ways of taking account of environments, whether through researchers or devices or environmental events. But these data are necessarily articulations of the ways in which environments are gathered and expressed through varying subjects—here, with subjects understood in the broadest possible way. Sensing systems generate distinct articulations of environmental relations within and through data and across sensing 'subjects/superjects.' Rather than take on a Kantian view of how 'the world emerges from the subject,' Whitehead with his 'philosophy of organism' seeks to understand how 'the subject emerges from the world,' thereby constituting a 'superject,' or a subject that is always contingent upon actual occasions and experience.[35] As Steven Shaviro notes in relation to Whitehead:

> There is always a subject, though not necessarily a human one. Even a rock – and for that matter even an electron – has experiences, and must be considered a subject/superject to a certain extent. A falling rock 'feels,' or 'perceives,' the gravitational field of the earth. The rock isn't conscious, of course; but it is affected by the earth, and this being-affected is its experience.

[36]

Sensor technologies are constitutive of sense—they too 'experience' the world and generate perceptive capacities. [37] Sensors that map in real-time a greater density of ecological relations could be seen as an attempt to work through a processual approach to environments, by focusing on interactions and even multiple modes of perception. At the same time, to identify a phenomenon as constituting sense data is to make a commitment to distinct 'forms of process,' so that environmental processes are selected and concretized in those forms. The process of selecting sense data involves capturing a moment in time, an 'instant,' that is then re-sutured with other data to form a pattern of any given ecological process. While approximating a more process-based and even real-time monitoring of environments, sensors are also productive of practices of selecting and interrelating discrete observations in order to arrive at an understanding of environmental process. The selection of temperature, vibration, light levels, humidity, and other measurements across primarily physical, although to some extent chemical and biological criteria, informs the instants that are sensed, the forms that are documented, and the processes that might be reconfigured.

The basis for developing facts within the sensing experiment then directly pertains to the forms and processes of experience that are generated and connected up across sensing subjects.[38] The emergence of data also requires subjects that can produce and parse this data. Subjects may be attuned or resistant to receiving data based on prior or emergent experiences. But data and the means of gathering data may also contribute to the possibilities for processing and integrating data. In this way, sense data may be generative of a superject where the experiences and perceptions generated are in turn formative of the subjects that experience. This runs counter to the notion that a founding subject is the entity that experiences. If, as Whitehead suggests, subjects are always superjects, then subjects are always necessarily distributed and emergent in relation to actual occasions.[39]

Approaches to media and sensation often focus on the ways in which technologies train or otherwise attune the human senses within a mediatory or prosthetic relation. But the interactions and processes of sense are arguably not fixed within sensory organs or technologies through which mediations are typically understood to take place. In this way, sensation is not primarily an inquiry into the relations between human subjects as they perceive nonhuman objects. Instead, the sensory relations within which sensors are mobilized give rise to a more ontogenetic understanding of perception, where sense and expressions of perception are articulated processually and across multiple sites and subjects of emergent sensation. In this way, new perceptual engagements are distributed across sensing capacities and engagements (perhaps similar to what Luciana Parisi has called 'technoecologies of sensation'), which give rise to distinct sensory processes, informational-material arrangements, and aesthetico-political possibilities.[40]

Such a condition resonates with what Patricia Clough refers to as the importance of focusing on 'an empiricism of sensation,' rather than 'an empiricism of the senses'[41] Technologies, including sensor systems, can be understood as generative ontologies that inform the experience and conditions that make sensation possible and changeable. Rather than studying 'the senses' as given, it may be more relevant to study experience and how distinct types of sensation become possible, and to consider further what modes of participation and relation these processes of sensation facilitate or limit. To bring this analysis back to sensor technologies, sense data are not simply items to be read and gathered as machinic observations of environments that scientists process. Instead, sense data are indications of a process of becoming sensible, where environments, humans and more-than-humans emerge as perceiving and perceivable entities.

Collaborative sensing

The modes of sensing that emerge within the context of ecological sensor applications might then begin to be described as collaborative sensing practices taking place across multiple subjects and through distinct processes of experience. On the one hand, these more emergent modes of sensing might be referred to as types of 'intimate sensing, as Stefan Helmreich has suggested in relation to fieldwork undertaken with oceanographers who employ a complex array of sensing technologies in their research. Sensing, in this account, is comprised of a research 'ecosystem,' and involves much more than a device focused on an object of study, since bodies enter into a circuit of sensation with instrumentation technologies. As Helmreich writes, 'These scientists see themselves as involved not so much in remote sensing as in intimate sensing.' Multiple forms of sensing emerge, across different technologies and researchers involved in studying ocean ecologies: 'The mediations are multiple and so are the selves.' [42] Influenced by Charles Goodwin's discussion of how forms of 'collaborative seeing' emerge within the space of a scientific vessel, [43] Helmreich develops an analysis of the sensing processes that becomes concretized and embodied within these body-environment-technology relationships, where new registers of feeling may even emerge through the repeated engagement with these devices. The multiple selves to which Helmreich refers most frequently refer back to scientists and crew members on ocean sensing expeditions, but by extending approach through a Whitehead-oriented understanding of experience it is possible to include even more expanded collaborative formations of sense. The experiences provided by and through more-than-human processes, as well as the processes that unfold within sense data, inform a different approach to what might constitute 'collaborative' modes of sensing.

Within the emerging area of posthuman media theory, sensation is increasingly understood as distributed in and through more-than-humans in the form of organisms and technologies, together with their environments. At times informed by Michel Foucault's well-known death-of-'man' statement, media scholars as far-ranging as Friedrich Kittler and Katherine Hayles, as well as Jussi Parikka and Matthew Fuller, have in different ways undertaken analyses of media that dispense with an assumed human subject as the principal site of meaning-making in order to recast the relations that emerge in and through media technologies.[44] As Hayles suggests, environmental modes of computation—RFID in her analysis—raise questions about the effects of 'creating an animate environment with agential and communicative powers.' Such technologies allow us to move toward 'a more processual, relational and accurate view of embodied human action in complex environments.'[45] Not just sensing, but also what counts as the 'human' shifts in these scenarios, since computational technologies typically now operate within parallel processes, and signal toward a multiplication rather than a centering of selves.[46]

The 'selves' that might be discussed as parallel, multiple, or collaborative within environmental sensing then extend not just to entities multiplied through nonhuman technologies, but also to the incorporation of nonhuman flora and fauna. Posthuman theories of subjects—or ecological approaches to subjects—are becoming increasingly well-established not just in media theory but also in philosophy and feminist studies, particularly as articulated in the work of Rosi Braidotti, who develops these notions through the work of Deleuze and Guattari (with an emphasis on the notions of ecology developed by Guattari). Making a case for the importance of posthuman and flat ontologies of subjects, Braidotti suggests that we begin to work with an 'environmentally bound subject' that is also 'a collective entity' because 'an embodied entity feeds upon, incorporates and transform its (natural, social, human, or technological) environment constantly.'[47] In this account, bodies and subjects are even understood as collective information machines of sorts. For Braidotti, 'techno-bodies' may be understood as 'sensors,' or 'integrated sites of information networks; vectors of multiple information systems.'[48]

Such an ecological approach to subjects resonates with Whitehead's discussion of subjects/superjects, where bodies-as-sensors are expressive and productive of environments. The sensing that takes places is a practice of processing and transforming. If human bodies are sensors, then by extension so too are the multiple more-than-humans that take in, express and transform environments. With these multiple formations of experience now at play across human and more-than-human subjects, it is then relevant to turn toward the specific distribution of environmental sensor networks in the James Reserve to consider how sensors are expressive of environments, what new environments and subjects emerge as experiencing entities, and how the sensing experiment is conducive to making these experiences possible.

Sensing an Experimental Forest
Returning now to a more detailed discussion of one embedded sensor network project, the CENS sensor installations at the James Reserve forest, I consider how this analysis of distributed sensing might be put to work in the context of this experimental project and test site. The CENS initiative is one of many sensor developments as discussed previously, and it is a well-known and frequently cited project for sensor research. Established in 2002 as a National Science Foundation Science and Technology Center, the CENS project is a collaboration between several California-based universities. The project, which finished in 2012, focuses on four key areas of research, including Terrestrial Ecology Observing Systems (TEOS); Contaminant Transport and Management; Aquatic Microbial Observing Systems; and Seismology. A fifth area of research, Participatory Sensing, has grown out of the project research into ecology and focused on how sensor applications may be used for citizen engagement in environmental and social issues.[49] This discussion focuses on the TEOS sensing deployments, which are primarily situated at the James Reserve (while the other study areas are located in a diverse range of sites). Participatory Sensing is a further area that I briefly address in the conclusion to this discussion.

The James Reserve ecological study site is in many ways an environment for developing experimental practices as well as for transporting laboratory techniques into the 'wild.' The fieldwork that I conducted at the James Reserve also moved from the laboratory to the field, as I first visited the CENS laboratory at UCLA where most of the sensor prototypes were developed, and then observed the sensors at work in situ at James Reserve. I held informal interviews with researchers involved in the CENS project, mapped the different locations and functions of sensors in the field at James Reserve, and compared the online records of sense data with the sites where sensors were installed. However, this is not a project of 'following the scientists,' which is by a now a well-established area within science and technology studies.[50] Instead, through fieldwork and within this paper I attempt to understand emerging processes and sites of sensing as they intersect with ecological practice and cultures of computation. Rather than focus exclusively on how ecologists use sensors to obtain scientific meaning or generate data or facts, I concentrate on James Reserve as a particular ecological research site, which emerges through a distribution of sensing processes across organisms, ecological processes, sensing technologies in the form of computational hardware and software, online interfaces, conservation infrastructures, resident scientists, environmental change, citizen scientists, publics, and visiting researchers.

The nearly 12-hectare and 1640-meter-high site is characterized by a complex intersection of ecosystems, 'including montane mixed conifer and oak forest, montane chaparral, wet and dry meadows, montane riparian forest, a perennial stream, and an artificial lake.'[51] Since James Reserve is located in a relatively remote wilderness setting, it is effectively 'off the grid,' and is a study area that generates its own solar power and has its own well for water. In this sensing lab or experimental forest, infrastructures are realigned, not as obvious allocations of roads, electricity and water, but rather as new arrangements of energy, sensation and observation. Sensing in the James Reserve is distributed not just across this experimental site, and at distinct locations for the study of ecological processes, but also across larger sensor networks. Many of the CENS James Reserve sensors are measuring phenomena over time, and enable researchers to study sequences of data that are fine-grained and relatively continuous in comparison to more discrete data sets, with data captures taking place in localized settings as frequently as every 15 minutes. Still other sensor test beds are in place to connect up to larger networks, including the National Ecological Observatory Network (NEON). Observations are successively gathered and joined up in far-reaching networks, such that sense data becomes an amalgamated and comparative networked infrastructure of ecological observatories for studying environments and environmental change.

CENS sensor systems are then developed and deployed within a larger project of collecting detailed data in order to respond more effectively to environmental challenges. Higher-resolution data promises to generate more effective models for predicting and managing environmental events. This 'new mechanistic understanding of the environment' involves a near-future commitment to developing a 'critical infrastructure resource for society' in the form of detailed environmental monitoring.[52] The promise to respond to crises more effectively develops not just through larger data sets, but also through more detailed data-gathering that is better tuned to detecting anomalies and extreme events, since most ecological data has largely consisted of documenting ecological conditions within a logic of averages and generalities. However, data expressive of average conditions do not capture the effects that major if singular disruptive events have on environments and rapidly shifting ecological relations and processes.[53] CENS and related projects such as NEON are then oriented toward the objectives of monitoring changing environmental processes, where an increasing number of disturbance events due to environmental change are contributing to the need to develop different practices and technologies for sensing environments. The expression and agitation of environments, which as Whitehead suggests 'seep' into all things, also turn up in and transform the sensing practices and technologies that monitor them. Instruments for capturing sense data are here specifically honed toward disturbance, as environmental change becomes more of a matter of concern within ecological study. At the same time, disturbance-detection rather than observation of norms begins to inform what counts as relevant sense data.

Machine ecologies

The sensors at work in the James Reserve within the TEOS group of research projects consist of everything from soil sensors that detect moisture levels; a Rhizotron installation of tubes that allows robotic cameras to capture images of root growth and CO2 sensors at three different soil depths to estimate soil flux; a bird-audio system involving sonic booms triggered by camera activity to capture woodpecker auditory data; weather stations for gauging microclimatic conditions; tree sap flow sensor systems; nest boxes with cameras and audio installed within bird boxes; pan-tilt-zoom tower cameras on 30-foot tall poles; and a MossCam web camera. At the time of this fieldwork, there were over 550 connected and untethered sensor nodes, as well as reconfigurable robotic mobile sensors working above and below ground, within waterways and across trees, capturing data on plants, animals, birds, soil, microclimate and more.[54] Sensor observations provide the ability to observe fungal growth patterns, soil CO2 production, the times at which plants shut down their CO2 fixing, and all manner of plant, animal and bird activity that typically takes place outside the scope of direct human observation.[55]

The initial proposal for this project made a bid to develop 'distributed sensor/actuator networks [that] will enable continual spatially-dense observation (and ultimately, manipulation) of biological, environmental, and artificial systems.'[56] Mid-way through the project, many of the initial proposals for comprehensively distributing a large number of small sensors within an area of study shifted to a practice of strategically deploying sensors in precise locations to study specific ecological activities, and developing a hierarchy of sensing platforms that span from small-scale motes to larger senses such as imaging robots on cables.[57] The sensor practices and arrangements developed in the James Reserve context are specific responses to site conditions and processes, so that phenomena to be observed have come to inform which sensors will be used and how. This points to a key aspect of the sensor systems: they are almost always physically proximate to that which they monitor. Sensors are distributed in the environment, and networks are developed and paired with environments.[58] Sensors in the field at James Reserve are wrapped around tree trunks in a concatenation of foil and cables; they are interspersed in the ground as arrays at regular intervals; and they are clustered at bird boxes to cross-correlate microclimate in relation to nesting at distinct locations.

The ways in which sensors are paired with environments are not a simple mirroring, however. Sensors proximate to roots and soil, for instance, do not stream all possible data all the time. Instead, sensor motes within a network talk to each other to coordinate data detected, processed and sent according to distinct algorithms. Part of this configuration has to do with energy efficiency, where motes are triggered to record events only at select times and are turned off during times of inactivity to save energy. Indeed, a key aspect of imagining the possibilities of sensors as environmental systems involves thinking through how it may be possible to realize 'pervasive sensing' without 'pervasive infrastructure,'[59] which primarily means not requiring a central electrical grid for power. The sensors at James Reserve are in part powered by a solar array that is the primary source of energy to power this elaborate sensing lab, which is supplemented by batteries, including motorcycle batteries, for distinct devices that typically transmit their sensory data via wireless connections.

Part of the algorithmic processing of sensor data then involves setting sensors to pick up, filter and amalgamate data within established ranges. The processing that sensors undertake is ad hoc and in situ, rather than a continual capturing and streaming of environmental activity. Each mote within a network is already set to detect some things and not others, to make correlations among certain data criteria, and to discard anomalies and redundancies according to predetermined phenomenal ranges. Sensor motes detect events within a specific range, and then process and communicate this data across short distances or hops to other sensors within the network for collection at sensor nodes. Data are typically fused and processed at each individual mote in order to make real-time streaming more efficient and effective.

While sensors are physically proximate to what they sense, that which is sensed and communicated travels through channels of algorithmic detection and processing. While on the one hand sensor applications are intended to record extreme events and anomalies, the algorithms that capture data have a tendency to smooth and fuse data at source in order to conserve energy and generate manageable quantities of data, which even with these filtering mechanisms can easily run to several million records per year per sensor patch. These syntheses are intended to turn data into 'high-level information,' where the multitude of records and raw data transform into something like observations or experience.[60] This transformation requires 'data reduction' in the form of 'in-network processing' that aggregates similar data and filters redundant data.[61] As Jeremy Elson and Deborah Estrin write,

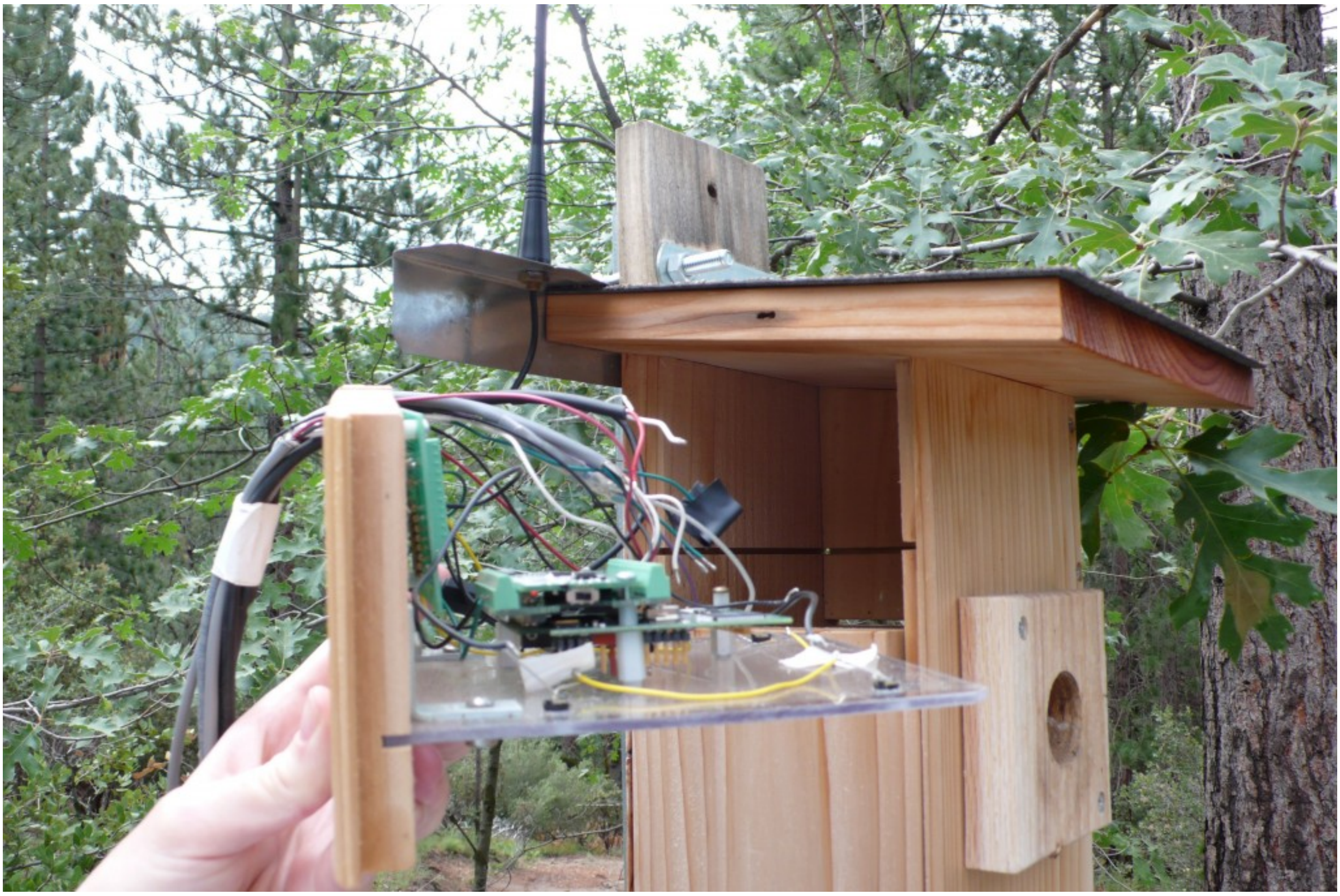
> For example, emerging designs allow users to task the network with a high-level query such as 'notify me when a large region experiences a temperature over 100 degrees' or 'report the location where the following bird call is heard.'

[62]

In this way, processes of filtering, aggregating, and selecting have already been put into place to turn sense data into relevant information. At the same time, these filters may not always capture intended phenomena. A researcher walking through the James Reserve forest may generate noise that is picked up on sonic booms, which through algorithmic parsing activates cameras to record activity. In this field of environmental sensing, researchers may fall within the data event-space of motion detection, but inaudible birds traveling in a different column of air might not be detected.

Processes of generating data are then also processes of making sense: the experiment is generative of modes of experience. These processes include how sensors are developed in the lab, tested in the field by technologists and scientists, merged within historic ecological study practices, read across new data sets, while also producing distinct insights into ecological relationships by connecting up multiple subjects. The architectures and algorithmic processes for relating sense data are a critical part of how sensor systems operate, and of articulating how sense data will come together into arrangements indicative of environmental and planetary processes.

Inevitably, the focus on gathering massive amounts of sense data raises issues related to the ontologies and incompatibilities of data. Sensor networks provide the basis for monitoring and acting upon environments, and yet the data and connections made across sensors are selectively captured and joined up, and are also subject to failure and incompatibility of data.[63] Different data standards, classification techniques, and dispersed practices inform the content and processing of data-spaces—a topic that Geoffrey Bowker among others has discussed at length.[64] Databases and data spaces are more than collections of objectively observable facts, but are embedded within and performed through infrastructures of sciences, governance and public outreach. On the one hand, there are issues related to how an entity becomes data, as Wolff-Michael Roth and G. Michael Bowen have discussed in relation to the digitization of lizards.[65] On the other hand, there are questions about what constitutes data (a lizard may seem to be a clear artifact of digitization, but when its habits and habitat become part of the sensed data, where does the organism begin and the environment leave off?). Data ontologies inform which data are collected, but they also inform possibilities of sense by giving rise to new actual entities and occasions of relevant sense data.



System as sensor and proxy sensing
In order to generate a more effective parsing of environmental phenomena, sensors are rarely used as individual devices that simply generate discrete sense data. Instead, multiple sensors and sense criteria within a sensor network are often brought together to form a composite picture of a distinct environment under study. Chemical analysis of pollution may provide readings on contaminant concentration levels, but additional sensors may also work out the direction and speed of contaminant travel, as well as the size of an affected area, by cross-correlating multiple sensor data. In this process of data fusion, the 'system is the sensor.'[66] Sensors working together within a network establish a computational network of correspondences, where the physical sighting, sensor type, coding, and correlating of data coalesce into an environment of sensor data that inform observations on the environment of study. When the 'system is the sensor' and the network operates as a sort of distributed instrument,[67] it is possible to generate models and forecasts of environmental processes, and through these sensor systems to act upon environments.

Sensor systems may also be proxies of the environments they sense. Sensors as proxies are not standing in for a more-real version of environments, but rather are sensory operations that mobilize environments in distinct ways. Proxy sensing could be understood to operate in multiple ways in the use of sensor systems for environmental monitoring. Sensor networks perform—and so transform—environmental systems. Data may be correlated across sensor types, or sensors may trigger other sensors to capture phenomena or trigger actuators to collect samples for later study.[68] Inferences can be made about phenomena through sensors and actuators, and sensors can be arranged through flexible, multiscalar platforms that investigate particular sensing relationships. As a CENS 'Distributed Sensing Systems' white paper notes, 'embedded sensing can involve a mix of observations with inherently different characteristics. For instance, it is common for systems to include multiple sensors, each with a different form of sensory perception or modality.'[69] This is the case in James Reserve, where seemingly traditional image and audio technologies provide a new way to 'sense' phenomena in the absence of direct biological sensors. While the majority of sensors now available are capable of detecting physical and chemical attributes, devices such as cameras become newly deployed as biological sensors in the absence of direct biological sensing capabilities, where physical and chemical sensors algorithmically set to filter for event detection automatically trigger cameras to record biological events.[70] Imager and audio modes of sensing are then activated within a computational network that mobilizes these forms of sensing as distinct and often proxy operations within a hierarchy of sensing. The possibility to articulate relationships and interactions within environments to a higher fidelity is then something that is generated and emerges through sensor applications that join up environments across sensor system hardware, software, databases, cyber-infrastructures, as well as distinct sites and the more-than-human processes that unfold there.

The proxy modes of sensing do not just extend to sensors triggering other sensors or actuators to perform sensing operations, but also include proxies that emerge vis-à-vis more-than-human processes. A not-uncommon technique within environmental study, where climate change in deep time may be studied through ice cores as proxies for past climate events, proxies within sensor-based environmental monitoring are mobilized to infer and detect traces of ecological processes. In the James Reserve, for instance, phenology is a central area of study. In order to capture seasonal relationships, organisms may be observed for the ways in which they 'process' environments. At the James Reserve, the perceptive capacities of Violet-Green Swallows and Western Bluebirds, in addition to Star Moss and other organisms, are placed under observation through web cams and Cyclops networked image sensors, which capture images and data related to these organisms often at least every fifteen minutes per day, if not more frequently.[71] The bird cams and MossCam, or web camera specifically monitoring the growth of Star Moss, generate a store of image data that can be compared to micro-local temperature and related data, as well as data captured throughout the James Reserve site. The birds' choice of a nesting location, or the failure to raise chicks due to absence of food or low temperatures, can be captured in this context where the birds' activities are made available as a sort of proxy sensor of phenological processes. Birds may provide key environmental sense data through computational networks that make sensible these registers of more-than-human experience. What is clear is that sensors do not just capture data, they shift the processes of sense across these multiple registers, so that more-than-human perceptive processes emerge in newly relevant arrangements.

Similarly, the Moss Cam generates images and daily records that contribute to a picture of seasonal patterns and 'event effects.' These effects might include lack of moisture in the summer, which contributes to mosses 'burning through' their CO2 reserves—in other words, higher temperatures can correlate to an increased release of CO2 by mosses, as they consume stored energy and move toward states of dehydration and dormancy. Here, what counts as 'sensing' is not a simple matter of observing mosses through a web camera over time, but instead involves observing how the moss is a sensor, or a biomonitor that is itself detecting and responding to changes in the environment.[72] The mosses' morphological changes to local conditions are an expression of an ecological relationship that is further entangled in the complex shifts of climate change. In this respect, the mosses may be expressing sensory responses to human-altered worlds, yet to understand more fully what those alterations involve, it is necessary to observe sensing organisms in order to register the effects of our actions. The delay and resonance within these environments is not as immediate as a typical sensory example might assume. Yet in this study, the ways in which sensing organisms 'take account' of environments multiply, where the sensory input and means of detection are distributed and computational.

In a sensor-based study of phenology, sense operations are distributed and collaborative. In these forms of collaborative sense, sensors experience and provide proxy experiences across a sensing system that generates distinct occasions of sense. But the collaborative qualities of sense emerge not through researchers primarily, but through the dynamic responses of organisms to environments, and the sensors that collect data through which algorithms query, filter and record these changes. The more dynamic sensory modalities that emerge in this relationship are examples of emerging ecological experiences and superjects, as discussed earlier. The timings at which plants leaf out, for instance, might even begin to disrupt and alter scientific models that expect seasonal timings to unfold at times established through prior empirical study. In these encounters and formations of sensory practice across organisms, ontologically prior categories of sense become more mutable and ontogenetic, where more-than-human modalities of sense indicate the shifting encounters of sense in which we are engaged. Sensor systems mobilize multi-located and multispecies processes of sensing, which in part enable the development of distinct capacities to sense change, where the scope of computational sensing and proxy sensing expands to include more-than-technological perceptual processes.

In an account of ubiquitous computing as distribution cognition, Hayles suggests that distributed computation could operate as machines for aiding and so enhancing human perception.[73] Here, however, computational devices are not augmenting human perception as such, and humans are not even the central perceptual processors toward which distributed sensation and computation might be directed. Instead, more-than-human proxy sensing points to the ways in which sensor technologies might be seen not as providing super-sensing or cognizing capabilities to supplement human modalities, but rather as technologies that filter, connect up and mobilize environmental relations in distinct ways, and so change what modes of sense humans may even experience. New ecological arrangements of subjects—and superjects—emerge through these sensory processes.

Environmental monitoring through sensor networks is a practice of making—and not just capturing—environments as process. Sensor networks are tuned to distributions of relations. They tune into discrete sense criteria, amalgamate these across sensor networks and through proxy modes of sensing, to make more evident and sensible environmental relations. Environmental monitoring through sensory networks mobilizes and generates environments in distinct ways by localizing computational processes of sensing within environments and across more-than-humans, while also articulating those relations through algorithmic processes for parsing data. As this process inevitably composes the possibility of sensing environments in particular ways, it also informs which participants and participatory modes of sensing register in the perceptive processes of sensor technologies. Such sensing practices, moreover, are replete with political effects. Within the context of sensor networks, the sensory arrangements that are identified within data may become the basis for identifying and protecting matters of concern;

or otherwise overlooking or missing those 'non-sensuous' background events that may still generate new arrangements, but which are not interpretable within present modes of sense data.[74]

Conclusion: Inventing Experience

From an experimental forest, this analysis of environmental sensing then turns back to Turing's countryside discussed previously, that apparently static backdrop through which sensing takes place. While Turing imagines a distributed sensing entity processing its bucolic surroundings, in this analysis of test sensors installed in a forest setting it becomes clear that the surroundings to be sensed are in flux and yet formative to establishing conditions and practices of sense. Through this reading, Turing's distributed computer becomes a superject, integrated with and formative of the environments and experiences it would decode. This is not a recursive logic, but as discussed throughout this paper, provides space for taking account of the abstractions and entities that lure feeling and settle into forms of environmental understanding.

The environment or milieu as differently understood by writers from Whitehead to von Uexküll, Canguilhem and Foucault, has been discussed as everything from the conditions of possibility to a zone of transformation and necessary extension within and through which experience is possible.[75] Within the work of von Uexküll, the now well-cited example of the tick that is provoked to act in relation to certain environmental cues, is referenced to signal both the ways in which sensation is tied to environments, and to suggest the species-specific coupling between these.[76] Sensing beyond the human subject can be figured through more-than-human agencies that unfold within environments. But if we take the provocations of Whitehead seriously, together with posthuman media theory and philosophy, then the milieu is not just a site where sensing joins up, but is also a transformative and immanent process where modes, capacities and distributions of sense emerge through the experiences of multiple subjects.

Any given milieu or subject/superject is then expressive not of static coupling as the work of von Uexküll suggests, but of creativity, as demonstrated in the work of Whitehead.[77] If inventiveness is a necessary part of perceptive processes, then the environment-as-agitation necessitates a more ontogenetic, collaborative and extensive understanding of sensing. In this way, perception might also move beyond the notion of hybridities or even mediations of sense, and instead focus on the sensing conditions and entities that emerge, as well as that which environmental perceptive processes make possible, and how inventive processes might further emerge.

The complex interactions that are the focus of study for environmental sensor systems are transformed through the perceptive processes that these systems generate. The distinct ways in which environments become or appear to be 'animate' are in part driven by the distributions of sense articulated through sensor devices and programs. The ecological relations that are to be discovered and studied are bound up with the detection of patterns within sense data. Sensor hardware and software do not simply gather sense data in the world, but are part of the process of perceptual possibility, both as more-than-human registers of perception and through making distinct relations sensible as subjects of ecological concern.

The possibility to relate and to make aspects of relations evident is an important aspect of sensor systems, with political and practical consequences. Sensation might be understood as distributed and automated on one level, yet on another level such automation in relation to environmental processes involves not just running scripted functions, but also addressing the open and indeterminate aspects of sensors in relation to environmental processes. This is one way of saying that whatever the computational program, sensors never operate strictly within a 'coded' space, but by virtue of drawing together alternative perceptive processes inevitably make way for a generative technics of environments.

There are then political implications to the implementing of sensor processes: relations are not just discovered, they emerge through these distinct computational sensing processes, and they also orient environmental practices and politics, where increased data and improved awareness of ecological relationships are expected to translate into an improved ability to manage environments and potentially prevent the spread of environmental damage. These crucial relationships emerge not just through practices of data collection and monitoring, as well as sharing and uploading data within larger networks, but also through drawing inferences across data sets that illuminate key ecological relationships that are to become the basis of concern or protection. On the one hand, as Whitehead suggests, that which counts as form or data is what endures within a 'process of composition,' which is expressive of 'historic character.'[78] What counts as empirical requires acts of 'interpretation,' but also describes a concrescence that continues to have the force of natural fact. Drawing on Locke, Whitehead notes, 'the problem of perception and the problem of power are one and the same, at least so far as perception is reduced to mere prehension of actual entities.'[79]

While Whitehead's analysis works across philosophic and cosmological registers, and does not directly address socio-political analysis of environments, his work does point toward potential translations to be made across experiencing subjects to political possibilities. As Shaviro suggests following on Whitehead, experience is a site of potential: 'It is only after the subject has constructed or synthesized itself out of its feelings, out of its encounters with the world, that it can then go on to understand that world – or to change it.'[80] In other words, as Whitehead notes, 'How the past perishes is how the future becomes.'[81] That which is sustained and that which emerges as a register of novelty are processes whereby experience may give rise to new experiences, interpretative practices and matters of concern.

In a different way, Foucault indicates through his discussions on the milieu that sensory arrangements are expressive of distributions of power, and involve making ongoing commitments to relations and ways of life.[82] Sensory processes that occur across subjects are then suggestive of aesthetico-political relations and possibilities for participation. Environmental monitoring through sensor networks is a technoscientific practice that pertains not just to the study of ecological relations, but also to emerging modes of participatory sensing and citizen science activity that rely on the use of the sensing capacities on mobile phones to track and gather data from environments. While there is not space here to discuss in detail the multiple developments in this area, the implications for sensory practices that emerge within an environmental monitoring context have relevance for thinking through the processual, relational and heterogeneous aspects of sensing. Given that the CENS research has moved 'out of the woods,' to citizen applications of sensing, while at the same time a whole host of citizen science applications including forest monitoring platforms are emerging to protect forests for conservation, how do forests, 'citizens,' more-than-humans and sensor technologies converge to invent new forms of politics that are attentive to present matters of concern, and those that are yet to come?

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applications for environmental engagement. More information on the project and related publications can be found at http://www.program-earth.org. (up)

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4. Ian F. Akyildiz et al., 'A Survey on Sensor Networks,' *IEEE Communications Magazine* (August 2002): 102–114; Gregory J. Pottie, and William J. Kaiser, 'Wireless Integrated Network Sensors,' *Communications of the Association for Computing Machinery* 43, no. 5 (2000): 51-58; Dana Cuff, Mark Hansen, and Jerry Kang, 'Urban Sensing: Out of the Woods,' *Communications of the Association for Computing Machinery* 51, no. 3 (2008): 24-33. . (up)
5. Alfred North Whitehead, *Process and Reality* (1927-28; repr. New York: The Free Press, 1985), 88-89. (up)
6. Stengers, 'A Constructivist Reading of Process and Reality,' 99. (up)
7. As N. Katherine Hayles writes in relation to distributed cognition of RFID tags, 'When we understand that humans are not the only cognizers who can interpret information and create meaning, we are free to imagine how a world rich in embodied contextual processes might be fashioned to enhance the distributed cognitive systems that surround us and that we ourselves are.' While this research is informed by this important posthuman media perspective that moves beyond human-centered approaches to computational technology, here I am interested to bring Whitehead into this discussion of distributions of sensing in order not to emphasize cognition (with its potential connection to consciousness), but rather to expand upon experience as a key way of drawing together multiple sensing entities. See N. Katherine Hayles, 'RFID: Human Agency and Meaning in Information-Intensive Environments,' Theory, Culture & Society 26, nos. 2-3 (2009): 69. (up)
8. Whitehead, Process and Reality, 20. (up)
9. Ibid., 88. (up)
10. Stengers elaborates on this sense of 'tuning' within experiments, and writes, 'the idea that experimentation appeals to facts as they are observed by means of experimental appliances only refers to the stabilized end-product of a difficult operation. As Andrew Pickering (1995) marvelously characterized it, in his *Mangle of Practice*, experimenters may well know in advance what they want to achieve – what, for instance, their appliance should detect. However, a long process of tuning will nevertheless be needed, within which nothing will be trusted, neither the human hypothesis nor the observations made. Indeed, the process of tuning works both ways, on human as well as on nonhuman agency, constitutively intertwining a double process of emergence, of a disciplined human agency and of a captured material agency.' Stengers, 'A Constructivist Reading of Process and Reality,' 96. (up)
11. Isabelle Stengers, 'The Cosmopolitical Proposal,' in *Making Things Public: Atmospheres of Democracy*, ed. Bruno Latour and Peter Weibel (Cambridge, MA: MIT Press, 2005), 994–1003. (up)
12. Etienne Benson, *Wired Wilderness: Technologies of Tracking and the Making of Modern Wildlife* (Baltimore, MD: Johns Hopkins University Press, 2010). (up)
13. Deborah Estrin, 'Reflections on Wireless Sensing Systems: From Ecosystems to Human Systems,' *Radio and Wireless Symposium*, IEEE (January 9-11, 2007): 1-4. (up)
14. Center for Embedded Networked Sensing (CENS), *Annual Progress Report* (University of California, Los Angeles, April 30, 2010). (up)
15. Gilman Tolle et al., 'A Macroscope in the Redwoods,' *SenSys'05* (San Diego, November 2–4, 2005); Jeremy Elson and Deborah Estrin, 'Sensor Networks: A Bridge to the Physical World,' in *Wireless Sensor Networks*, ed. Cauligi S. Raghavendra, Krishna M. Sivalingam, and Taieb Znati (Norwell, MA: Kluwer Academic Publishers, 2004): 3-20. (up)
16. This paper focuses on sensor applications for ecological study. However, this by no means cover the entirety of sensor applications for environmental uses and beyond, including agricultural management and energy saving in buildings. A whole range of automated environments is emerging through sensor applications, which is the subject for future study through the Program Earth research topic area. (up)
17. Robert Szewczyk et al., 'An Analysis of a Large Scale Habitat Monitoring Application,' *Proceedings of the Second ACM Conference on Embedded Networked Sensor Systems* (Baltimore, MD: November 2004): 214-226. (up)
18. The U.S. Long Term Ecological Research Network (LTER), accessed April 3, 2012, http://www.lternet.edu/; National Ecological Observatory Network (NEON), accessed April 3, 2012, http://www.neoninc.org/. (up)
19. Paul N. Edwards et al., 'Introduction: An Agenda for Infrastructure Studies,' *Journal of the Association for Information Systems* 10, no. 5 (May 2009): 364-374; Dave Schimel et al., '2011 Science Strategy: Enabling Continental-Scale Ecological Forecasting,' National Ecological Observatory Network (NEON, 2011). (up)
20. Microsoft Research, 'SenseWeb,' accessed April 3, 2012, http://research.microsoft.com/en-us/projects/senseweb/; Cosm (formerly Pachube), accessed August 7, 2012, https://cosm.com/. (up)
21. Michael Lehning et al., 'Instrumenting the Earth: Next-Generation Sensor Networks and Environmental Science,' in *The Fourth Paradigm: Data-Intensive Scientific Discovery* (Microsoft Research, October 2009). (up)
22. Nokia, 'Sensor Planet,' accessed April 3, 2012, http://research.nokia.com/page/232; IBM, 'A Smarter Planet,' accessed April 3, 2012, http://www.ibm.com/smarterplanet/uk/en/; HP Labs 'Central Nervous System for the Earth (CeNSE),' accessed April 3, 2012, http://www.hp.com/hpinfo/globalcitizenship/environment/tech_gallery/cense.html?jumpid=reg_r1002_usen; Planetary Skin Institute, accessed April 3, 2012, http://www.planetaryskin.org/. (up)
23. For a discussion of the multiple parties invested in ubiquitous computing, including governments, see Christian Nold and Rob van Kranenburg, 'The

Internet of People for a Post-Oil World,' *Situated Technologies Pamphlets 8* (New York: The Architectural League of New York, 2011). (up)

24. While there is not space within this paper to discuss these developments within sensor systems, for a more extensive discussion of how emerging sensing technologies and practices might be understood as forms of environmentality see Jennifer Gabrys, 'Programming Environments: Environmentality and Citizen Sensing in the Smart City,' forthcoming. This paper draws on Foucault's reference to environmentality in Michel Foucault, *The Birth of Biopolitics: Lectures at the Collège de France 1978-1979*, translated by Graham Burchell (2004; repr. Palgrave MacMillan, New York, 2008). (up)
25. For a discussion of earlier attempts to program environments with sensors through the prototypical if largely hypothetical technology of smart dust, see Jennifer Gabrys, 'Telepathically Urban,' in *Circulation and the City: Essays on Urban Culture*, ed. Alexandra Boutros and Will Straw (Montreal: McGill-Queen's Press, 2010), 48-63. (up)
26. CENS, 'Annual Progress Report,' 3. (up)
27. Adrian Mackenzie discusses this issue of how relations or itineraries are drawn through software in Adrian Mackenzie, *Cutting Code: Software and Sociality* (New York: Peter Lang, 2006). See also, Matthew Fuller, *Behind the Blip: Essays on the Culture of Software* (Brooklyn, NY: Autonomedia, 2003). (up)
28. Mark Weiser, 'The Computer for the 21st Century,' *Scientific American* 265, no. 3 (1991): 94–104. (up)
29. Alan Turing, 'Intelligent Machinery,' in *Mechanical Intelligence: Collected Works of A.M. Turing*, ed. Darrel C. Ince. (1948; repr. Amsterdam: North Holland, 1992), 117. (up)
30. Turing, 'Intelligent Machinery,' 117. (up)
31. Alfred N. Whitehead, *Modes of Thought* (1938; repr. New York: The Free Press, 1966); Brian Massumi, *Semblance and Event: Activist Philosophy and the Occurrent Arts* (Cambridge, MA: MIT Press, 2011). (up)
32. Whitehead, *Modes of Thought*, 158; Isabelle Stengers, *Thinking with Whitehead: A Free and Wild Creation of Concepts*, trans. Michael Chase (Minneapolis: University of Minnesota Press, 2011), 352-353 (up)
33. Whitehead, *Modes of Thought*, 138. (up)
34. Whitehead, *Modes of Thought*, 158. And as Stengers writes, 'We do not know how a bat, armed with its sonar, or a dog, capable of tracking by smell, 'perceive 'their' world. We can identify the features they discriminate, but we can only dream of the contrast between 'that which' they perceive and what they are aware of. All we "know" is that their experience is, like ours, highly interpretative, and that, like ours, it has solved an extraordinarily delicate problem: to give access, in a more or less reliable way, to what it is important to pay attention to.' Paying attention is 'the interpretative choice from which our experience has issued.' Isabelle Stengers, *Thinking with Whitehead: A Free and Wild Creation of Concepts*, trans. Michael Chase (Minneapolis: University of Minnesota Press, 2011), 338. (up)
35. Whitehead, *Process and Reality*, 88. (up)
36. Steven Shaviro, *Without Criteria: Kant, Whitehead, Deleuze, and Aesthetics* (Cambridge, MA: MIT Press, 2009), 21. (up)
37. While this notion of distributed experience can be found within Whitehead's writings, it also is a prior concept developed by William James in relation to radical empiricism. Adrian Mackenzie takes up the latter concept in relation to wirelessness to discuss how wireless technologies unfold these distributions of experience. See Adrian Mackenzie, *Wirelessness: Radical Empiricism in Network Cultures* (Cambridge, MA: MIT Press, 2010); and William James, *Essays in Radical Empiricism* (1912; repr. Lincoln, NE: University of Nebraska Press, 1996). (up)
38. For a more extended discussion on the development of 'facticity,' see Michael Halewood and Mike Michael, 'Being a Sociologist and Becoming a Whiteheadian: Toward a Concrescent Methodology,' *Theory, Culture & Society* 25, no. 4 (2008): 34; and Stengers, 'A Constructivist Reading of Process and Reality.' (up)
39. Thanks are due to Mike Michael for conversations that have led to these points. (up)
40. Luciana Parisi, 'Technoecologies of Sensation and Control' *Deleuze and Guattari and Ecology*, ed. Bernd Herzogenrath (Basingstoke: Palgrave Macmillan, 2009): 182-200. (up)
41. Patricia Ticineto Clough, 'The New Empiricism: Affect and Sociological Method,' *European Journal of Social Theory* 12, no. 1 (2009): 51. (up)
42. Stefan Helmreich, 'Intimate Sensing,' in *Simulation and Its Discontents*, ed. Sherry Turkle, (Cambridge, MA: MIT Press, 2009), 130-132. (up)
43. Charles Goodwin, 'Seeing in Depth,' *Social Studies of Science* 25, no. 2 (1995): 237-274. (up)
44. Michel Foucault, *The Order of Things: An Archaeology of the Human Sciences* (1970; repr. London: Routledge, 1994); Friedrich Kittler, 'Thinking Colors and/or Machines,' *Theory, Culture & Society* 23, no. 7-8 (2006): 39-50; N. Katherine Hayles, 'Computing the Human,' *Theory, Culture & Society* 22, no. 1 (2005): 131-151; Jussi Parikka, *Insect Media: An Archaeology of Animals and Technology* (Minneapolis: University of Minnesota Press, 2010); Matthew Fuller, 'Boxes towards Bananas: Dispersal, Intelligence and Animal Structures,' in *Sentient Cities: Ubiquitous Computing, Architecture, and the Future of Urban Space*, ed. Mark Shepard (Cambridge, MA: MIT Press, 2011), 173-181. (up)
45. N. Katherine Hayles, 'RFID: Human Agency and Meaning in Information-Intensive Environments,' *Theory, Culture & Society* 26, nos. 2-3 (2009), 48. (up)
46. Brian Rotman, *Becoming Beside Ourselves: The Alphabet, Ghosts, and Distributed Human Being* (Durham: Duke University Press, 2008). (up)

47. Rosi Braidotti, *Transpositions: On Nomadic Ethics* (Cambridge: Polity, 2006), 41. See also Felix Guattari, *Chaosmosis: An Ethico-Aesthetic Paradigm* (Bloomington: Indiana University Press, 1995). (up)
48. Braidotti, *Transpositions*, 96-97. (up)
49. CENS, 'Annual Progress Report,' 3. (up)
50. Bruno Latour, *Science in Action: How to Follow Scientists and Engineers through Society* (Cambridge, MA: Harvard University Press, 1987). (up)
51. Michael P. Hamilton et al., 'New Approaches in Embedded Networked Sensing for Terrestrial Ecological Observatories,' *Environmental Engineering Science* 24, no. 2 (2007): 192-204. (up)
52. Jeffrey Goldman et al., 'Distributed Sensing Systems for Water Quality Assessment and Management,' White Paper (Washington DC: Woodrow Wilson International Center for Scholars, Foresight and Governance Project, February 2007), 3. (up)
53. Philip W. Rundel et al., 'Tansley Review: Environmental Sensor Networks in Ecological Research,' *New Phytologist* 182 (2009): 589-607. (up)
54. CENS, 'Terrestrial Ecology Observing Systems,' accessed July 15, 2008, http://research.cens.ucla.edu/areas/2007/Terrestrial/default.htm. (up)
55. CENS, 'Annual Progress Report,' 6. (up)
56. CENS, 'Center for Embedded Networked Sensing,' NSF Science and Technology Centers proposal, 5. (up)
57. Estrin, 'Reflections on Wireless Sensing Systems,' 2. (up)
58. Goldman et al., 'Distributed Sensing Systems,' 12. (up)
59. Elson and Estrin, 'Sensor Networks,' 2. (up)
60. Elson and Estrin, 'Sensor Networks,' 7. (up)
61. Ibid., 10. (up)
62. Ibid., 7. (up)
63. Inevitably, incompatibilities within data sets are not the only issues with sensors. Given that the embedded sensors are prototypes and tested 'in the wild,' the devices at times cease to function as intended, whether due to mechanical failure, calibration issues, or bugs in the code. Given that the CENS project has also come to an end, some sensors may cease to function and breakdown over time. For a more extended discussion on the material processes of electronics as they break down, see Jennifer Gabrys, *Digital Rubbish: A Natural History of Electronics* (Ann Arbor, MI: University of Michigan Press, 2011). (up)
64. Geoffrey C. Bowker, 'Biodiversity Datadiversity,' Social Studies of Science, 30, no. 5 (2000): 643-683. For a detailed discussion of data issues that have emerged specifically in relation to the CENS project, see Christine L. Borgman, Jillian C. Wallis, Noel Enyedy, 'Little Science Confronts the Data Deluge: Habitat Ecology, Embedded Sensor Networks, and Digital Libraries,' *International Journal on Digital Libraries* 7, no. 1 (2007): 17-30. (up)
65. Wolff-Michael Roth and G. Michael Bowen, 'Digitizing Lizards: The Topology of 'Vision' in Ecological Fieldwork,' *Social Studies of Science* 29, no. 5 (1999): 719-764. (up)
66. Goldman et al., 'Distributed Sensing Systems,' 10. (up)
67. Tolle et al., 'A Macroscope in the Woods.' (up)
68. Goldman et al., 'Distributed Sensing Systems,' 6. (up)
69. Ibid., 19, emphasis in original. (up)
70. Estrin, 'Reflections on Wireless Sensing Systems,' 2. (up)
71. CENS, 'Annual Progress Report,' 29 (up)
72. Josh Hyman, Eric Graham, and Mark Hansen, 'Imagers as Sensors: Correlating Plant CO2 Uptake with Digital Visible-Light Imagery,' *Proceedings of the 4th International Workshop on Data Management for Sensor Networks* (Vienna, Austria, September 23-28, 2007). (up)
73. Hayles, 'RFID,' 48-49. (up)
74. Alfred N. Whitehead, *Adventures of Ideas* (1933; repr. New York: The Free Press, 1967), 180-181; Whitehead, *Modes of Thought*, 30, 157. (up)
75. Whitehead, *Modes of Thought*; Jacob von Uexküll, *A Foray into the Worlds of Animals and Humans*, trans. Joseph D. O'Neil (1934; repr. Minneapolis: University of Minnesota Press, 2010); Georges Canguilhem, 'The Living and Its Milieu,' trans. John Savage, *Grey Room* 3 (Spring 2001): 6-31; Foucault, The Birth of Biopolitics. (up)
76. von Uexküll, *A Foray into the Worlds of Animals and Humans*, 44-46 (up)
77. Whitehead, *Process and Reality*, 20-21. (up)
78. Whitehead, *Modes of Thought*, 89-90. (up)
79. Whitehead, *Process and Reality*, 58. (up)
80. Shaviro, *Without Criteria*, 25. (up)
81. Whitehead, *Adventures of Ideas*, 238. (up)
82. Foucault, *The Birth of Biopolitics*. (up)